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ISABE 99-7284

DIRECT FUEL COOLED COMPOSITE STRUCTURE

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ABSTRACT

One of the more challenging aspects of hypersonic propulsion systems is the development of lightweight structure that can withstand the severe conditions associated with flight up to Mach 8. Currently, the Pratt & Whitney expendable scramjet engine concept utilizes a metallic combustor, based upon high temperature alloys with integral, endothermic fuel cooling. There is the potential for reduction in propulsion system weight and cost, and increase in thermal management margin if these high density metal alloys can be replaced with advanced composite materials. Pratt & Whitney (P&W) and ONERA (Office National d'Etudes et de Recherches Aerospatiales) are prime contractors in a joint U. S. Air Force (USAF) / French Directeur Generale d'Armements (DGA) sponsored advanced technology demonstration program that combines direct fuel cooling with a hot structure manufactured from advanced composite materials. The four-year Advanced Combustion Chamber Concepts (AC3) Program proposes to combine these two innovative technologies in two proof-of-concept demonstrations. P&W is supported in this program by the United Technologies Research Center (UTRC), and ONERA is supported by SEP (Societe d'Europeenne de Propulsion) Division of SNECMA (Societe National d'Etudes et de Construction de Moteurs d'Aviation) Corporation. Phase 1 of AC3 will be a sector panel test, while Phase 2 is planned as a fabrication and test of a 2-D scramjet combustor.

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INTRODUCTION

For a scramjet engine, the operational environment is so severe that thermal protection and accommodation are controlling requirements in the design. However, the means by which to accommodate thermally induced loads typically have significant penalties on weight, cost, and operability. High temperature nickel alloys, cobalt alloys, and refractory alloys have the drawbacks of weight and other problems. Thermal protection systems such as tiles or rigid foams cannot be applied to scramjet combustor flowpaths. Ablative coatings are not attractive because of the non-uniform burn-off of the ablative, and the effect of this burning on the supersonic combustion process. Active cooling is required and the structure cannot be air cooled due to the resulting temperature when stagnating this high speed flow to near static conditions.

The fuel, however, provides an attractive coolant source. The thermal margin associated with cooling the hot structure directly with the fuel can be limited however when using storable hydrocarbon fuels; this limitation being driven by the formation of coke. The thermal margin can potentially be increased by combining two approaches for accommodating thermal loads in a scramjet engine, composite materials and direct fuel cooling. Such a combination has the potential to increase design and operating margin at currently projected operating Mach numbers (up to Mach 8). Or it can allow, for the current level of margin, operation to higher Mach numbers with storable hydrocarbon fuels.

The ability to combine direct fuel cooling with storable hydrocarbon fuels and hot structure manufactured from advanced composite materials may result in significant weight, cost and thermal margin benefits for hypersonic propulsion systems.

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DISCUSSION

Combustion and turbine flowpath requirements for advanced gas turbine engines are responsible for the advancements made in high-temperature metal alloys and innovative cooling schemes. However, the operational environment of a scramjet engine is one of the most severe known for airbreathing engines, and these gas turbine-developed materials generally do not have the capability to survive unaided in such an environment. Without supplementary methods to reduce these thermal effects, the materials cannot maintain sufficient strength for the engine to survive. At low Mach number flight conditions, air can be taken on board and utilized as a coolant. Once flight speeds exceed Mach 4 however, ram air cannot be used for cooling, because of the high stagnation temperature. At Mach 4 conditions, for example, the stagnation temperature is approximately 4.2 times static temperature, resulting in a cooling air temperature of slightly less than 1200 F (650 C). Even if this high temperature air could be used for cooling, its density is low and a large volume of this air would need to be captured with a corresponding penalty in vehicle size.

Historically, the method employed during the design of such propulsion systems was to simply use higher temperature alloys. These materials would be selected for having material properties at elevated temperatures and were typically nickel or cobalt alloys like the INCO-class alloys (e.g. INCO-625), Haynes 188, Waspalloy, and others. One drawback of this class of material is the high unit density involved (typically 0.28 to 0.33 lb/cu. in., or 7.8 to 9.1 g/cc). Also, while being an improvement over alloys of lower maximum useful temperature, they still can require some degree of cooling or shielding from excessive thermal loads. But these materials have several distinct advantages. They are not much higher in costs, relative to lower capability alloys. They generally are readily available from production facilities and specialty mills. They are well characterized, and are very repeatable between production lots. Also, being a monolithic material, load path direction (structural or thermal) is not a concern.

Another metallic option is that of refractory metals such as columbium/niobium, tantalum and tungsten. These alloys have a somewhat higher operational temperature capability with reduced cooling requirements, but with a penalty of slightly higher density. These materials are also considerably more expensive, and are not as readily available due to long lead times required for production. They are also very susceptible to oxidation erosion at high temperatures

unless a protective coating is applied to the exposed surfaces.

While metal alloys are the current baseline, it is clear that for extreme temperatures such as those associated with hypersonic propulsion systems, more capability in terms of strength, minimized cooling requirements, and avoidance of detrimental chemical reactions is desirable. The next class of materials available for hypersonic designs, that potentially satisfy the simultaneous requirements of high strength, high temperature resistance, lower cooling requirements, and lower weight are composite materials.

Composite materials offer the combined advantages of low density (typically in the range of 0.07 to 0.10 lb/cu. in., or 1.9 to 2.8 g/cc) and low thermal conductivity (ranging from 3.5 to 7.5 Btu/h-ft-F, at 1200 F, or 6.1 to 13 W/m-C). However, composites are not monolithic materials, hence load direction and material/fiber orientation is of prime importance when developing a design from both mechanical/structural and thermal standpoints. This apparent limitation, in reality, offers the added flexibility to tailor the composite material within production limits, to best address operational requirements.

Composite materials, within the constraints described above, provide a viable solution to the design of a direct fuel cooled scramjet engine, but there are significant limitations of composite materials that must be addressed. One concern is protection from oxidation in the combustion flowpath. Due to the nature of flow contraction, with minimized velocity drop within the scramjet combustor, even at an equivalence ratio of 1, the fuel distribution is not uniform throughout the flowpath. A boundary layer of hot air, not available for the combustion process, bathes these surfaces. Similarly, there will be stagnant air in the backstructure of the scramjet engine, which will be heated during flight, albeit to lower temperatures than within the combustor. Since the carbon fibers are the load-carrying member in most composite materials, exposure to hot oxygen will gasify these fibers, reducing the mechanical strength of the composite. This can be prevented through the use of anti-oxidation coatings. Such coatings must bond to the substrate tenaciously and possess very close to, if not the same, thermal expansion characteristics to preclude cracking and separation of the coating from the substrate. Parallel with this issue of oxidation protection is the issue of porosity of composite materials, or leakage and absorption. Composite materials are known to absorb liquids to various degrees, and these liquids can either be trapped in the matrix causing it to swell, or to seep

through. Since light hydrocarbon gases are produced during the endothermic reforming process, the control of fuel leakage (both liquid and gas) assumes even greater importance. This issue is similarly addressed through the use of coatings on the substrate as well as a secondary option of metallic enclosures and metallic isolation systems (i.e. metallic tubes to line flow passages, backstructure metallic covers, etc.).

Composite materials provide the potential for a significant number of payoffs for scramjet engine systems. Composite materials such as carbon silicon carbide (C/SiC), depending on the level of densification and other factors, have approximately 25 percent of the density of monolithic nickel and cobalt alloys. This lower density, however, does not translate automatically into a four-to-one reduction in weight due to certain properties limitations with composite materials such as minimum gauge or thickness (the smallest thickness that can be produced which retains bulk mechanical properties) and interlaminar shear (failure between plies in the structure being produced) as well as other considerations. However, relative to high-temperature metal alloys, it should be possible to attain weight reductions approaching 50 percent of comparable metallic configurations. Part of this weight reduction will be due to the lowered density of composites, but part will also be due to tailoring of load paths via fiber orientation, types of weave, etc. which cannot be performed with monolithic materials. This ability to tailor the composite material, to develop the most advantageous structure (greatest load carrying capability for the least weight), forcefully brings home one other important point and that is the necessity of a "clean sheet" design. To merely take an existing metal design, and produce it from composite material, is to not take the fullest advantage of composites.

Composite materials also have several desirable characteristics in the area of thermal conductivity and heat transfer. This class of material, generally has thermal conductivities on the order of 25 to 33 percent of metal alloys, but can be tailored via weaves, densification, and other means so that conductivities not only approach that of metal alloys, but can be made "directional". In an application such as direct fuel cooled structure, it can be very desirable to have lowered thermal conductivity. This can allow operation at a given design Mach number with extra cooling system margin relative to a metal design. The other possibility is that for a given coolant temperature, being able to operate a propulsion system at a higher flight Mach number. Both options are open to the designer, based on definition of system requirements and mission profile.

Also, it is possible that with large production runs of expendable scramjet engine hardware fabricated from advanced composite materials, that there will be a reduction in propulsion system cost relative to designs based upon high temperature nickel, cobalt, and refractory alloys. However, the potential for cost reduction is highly dependent on production techniques, production run sizes, the ability to combine multiple functions into fewer components, etc. In short, cost savings will be demonstrated on an overall system basis, rather than on a one-for-one component comparison basis.

Even composite materials have thermal limits, albeit that these operating limits can be much higher than for uncooled metals. The next logical step is to combine this class of material with direct fuel cooling in a synergistic manner. While this can be accomplished by various schemes, and with different fuels - including cryogenic fuels - the focus of the following discussion will be on a storable hydrocarbon fuel, in which the cooling capability is augmented by an endothermic reforming process.

The process of endothermically decomposing a fuel for cooling a propulsion structure with a storable hydrocarbon fuel is analogous to the reforming process used to convert crude petroleum stock into useful fuels. In the latter process, the raw petroleum stock is heated while in contact with catalytic material, causing the long-chain hydrocarbon molecules to break down, in a planned and repeatable manner, into smaller, lighter hydrocarbon molecules that are desirable for fuels, plastics, etc. This reforming process is tailored in that the type of petroleum stock is matched to a type, or types, of catalyst to produce these desired end products. This selectivity of the catalyst is very important in this process as the reforming process is generally carried out over several batch runs, each run producing different and successively lower molecular weight products. To obtain the desired end products, whether it be a paraffin, an alkene, etc., it becomes critical to match the catalyst to the stock in terms of chemical reaction, pore sizes (for zeolite catalysts), poisoning tolerance (for precious-metal catalysts), selectivity/products produced, and other considerations.

While similar to the above-described process, endothermic fuel cooling for propulsion applications differs in one important respect and that is that the primary goal is the absorption of heat. In the endothermic decomposition process, a liquid hydrocarbon fuel is catalytically reformed into lower molecular weight hydrocarbons, absorbing a significant

amount of heat in the process (as much as 700 Btu/lbm, or 390 cal/g). In turn, these hydrocarbon gases have a number of desirable characteristics from a propulsion standpoint. They have a high lower heating value, they have very low ignition delay, a flame front in such a fuel-air mixture will propagate very rapidly across the combustion flow field, and with potentially lower emissions. All of these attributes being relative to the parent liquid hydrocarbon fuel used in this catalytically-driven reforming process. This cooling process clearly allows the use of currently available metal alloys in an environment that by its severe nature, would preclude the use of the same materials in an uncooled fashion.

This process of directly cooling practical geometry hot structure via the exploitation of a catalytically-driven endothermic process was demonstrated at UTRC during Task Order 002 of the P&W-prime "High Mach Turbine Engine" (HiMaTE) program (NAS3-26052). HiMaTE, a joint NASA-Glenn Research Center/U. S. Air Force Research Laboratory sponsored contract, is a technology development program, designed to demonstrate high-payoff technologies for hypersonic propulsion systems. In this particular task order, two types of endothermic fuel reactors, known as catalytic heat exchanger/reactors, or CHER's, were demonstrated with wall-supported catalysts. One type of CHER was a single-element reactor in which a small diameter metallic tube (typically 0.058 inches [1.5 mm] diameter) was used to simulate a single flow passageway of a larger CHER. These single-element CHERs were used to characterize fuel/catalyst reaction products, heat absorption, catalyst performance, etc. The second type of CHER was a panel representative of a sector of typical direct fuel-cooled structure such as would be used in a hypersonic propulsion system. This sector panel, which was constructed from INCO-625 nickel alloy, was a sandwich consisting of two face sheets, 0.050 inches (1.3 mm) thick, between which was brazed a corrugated 0.005 (0.13 mm) inch thick foil. This type of construction formed a series of parallel flow passageways, approximately 0.041 inches (1 mm) wide by 0.050 inches (1.3 mm) high, running the length of the sector panel. These passageways were then coated with catalytic material. This configuration provided 22 such flow passageways per lineal inch of width. In this task order, several catalysts were evaluated with the single-element CHERs, leading to the selection of a particular zeolite. Successful demonstrations of the CHER sector panels, at extreme conditions representative of what would be experienced by an accelerator gas turbine engine for a hypersonic vehicle, were completed with NORPAR-12 (an all-paraffinic

blend, industrial solvent produced by EXXON Corp.) as the fuel.

Subsequent programs at UTRC as well as at P&W, have expanded the knowledge base beyond that of this seminal work performed in the HiMaTE program to include demonstration of cooling such hot structure operating in a scramjet combustor environment. This was demonstrated in the UTRC-prime, U. S. Air Force-sponsored, "Scramjet Component Technology" (SCT) Program (F33615-90-C-2093), which was followed by the current P&W-prime, U. S. Air Force-sponsored "Hypersonic Scramjet Engine Technology" (HySET) Program (F33615-96-C-2694).

In the current HySET program, the scramjet propulsion system is being designed, developed, and demonstrated by the P&W-led team consisting of P&W and UTRC. The scramjet configuration developed for this program is a rectangular cross-section, fixed geometry, metallic combustor, designed to operate on hydrocarbon fuel, from Mach 4 to Mach 8. This metallic combustor is regeneratively cooled via the previously described endothermic decomposition process. In this engine configuration, the combustor has its walls manufactured from a structure consisting of an INCO-718 webbed backstructure to which is diffusion bonded a Haynes 188 alloy fuel plate. The fuel passageways are machined into this fuel plate. This type of fuel-cooled structure, as with the structure demonstrated in the previously described HiMaTE program, are plate-fin type CHER units. In a simplified description of the fuel cooling circuit, these panels are used in a parallel-flow configuration relative to the combustion flowpath. The liquid hydrocarbon fuel enters at the rearmost end of the bodyside combustor wall, flowing forward to the inlet, and then being distributed into the other three remaining walls, i.e., the two sidewalls, and the cowl. The fuel is catalytically reformed within this structure by the catalyst deposited within the panels. The resulting gaseous hydrocarbon fuel is then collected at the end of the cooling circuit and routed to the injectors for combustion.

A metallic CHER of this design has been tested in the Mach 8-capable scramjet combustor rig at UTRC and its performance and heat transfer capability has been characterized over a number of test runs.

While this demonstrated metallic configuration has performed well in testing to date, it is a first-generation device for a scramjet engine, and as such has several areas that can benefit from further development and refinement to make it more viable for a flightweight system. The current HySET scramjet engine

configuration is designed for an expendable application, in which cost and weight are major considerations in addition to the primary goal of performance. For the current HySET configuration, this metallic combustor is estimated to constitute nearly half of the total propulsion system weight. Also, this combustor design is more than two-thirds of the currently estimated propulsion system cost. Similarly, this panel design, with the design limits and the attendant level of thermal capacity associated with these alloys, is low in thermal "margin" at the two most severe flight conditions in the anticipated flight trajectory. The acceleration point has the most severe aerodynamic and combustion heating, but simultaneously has a higher fuel flow than the cruise condition to provide sufficient cooling of the combustor structure. The cruise point has lower aerodynamic and combustion heating, but also much lower fuel flow relative to the accel condition. With the coking limits determined at UTRC under single-element tests, there is relatively little margin to accommodate additional heat loads for this engine.

Clearly, if there was a method or approach by which these two advanced technologies, advanced composite materials and endothermic fuel cooling, could be combined, there would be a significant payoff for expendable scramjet engines. This payoff would, with further development, become applicable to advanced lower speed propulsion systems such as man-rated gas turbine engines and hypersonic propulsion systems, as well as rocket motors. Therefore, the U. S. Air Force and the French Directeur Generale d'Armements (DGA) initiated a collaborative technology demonstrator program, the Advanced Combustion Chamber Concepts (AC3) Program (F33657-95-D-0093/0012). This program is being executed by P&W and UTRC in the United States, and by ONERA and SEP in France.

The goals of the AC3 program are twofold. The first goal is to perform a proof-of-concept demonstration of a catalytic heat exchanger/reactor (CHER) manufactured from composite material in which endothermic cooling occurs, while operating in a scramjet environment. The second goal is to fabricate and test a full 2-D scramjet combustor component constructed in the same manner as the panels demonstrated earlier. The program is four years in length, consisting of two phases, as described previously. The program is designed to merge these two technologies in a building block approach so as to minimize the associated risk of advanced technology development as much as possible.

In Phase 1 of AC3, the proof-of-concept demonstration phase, the overall approach is to establish basic component characterization, at the material level as well as the operational level. All four contractors, P&W, ONERA, UTRC, and SEP will participate in the design activities of both a direct fuel cooled scramjet engine concept made from composite material, as well as the design of the composite material CHER panels. SEP will perform all screening tests of candidate materials such as carbon/carbon (C/C) and carbon/silicon carbide (C/SiC), anti-oxidation coatings, anti-porosity coatings, and brazing and bonding compounds. P&W will perform all catalyst compatibility testing to ensure that the catalyst and binder agents are adherent and chemically stable with the candidate substrates, in both the coated (anti-oxidation and anti-porosity coatings) and uncoated states. Fabrication samples will be produced by SEP and tested by P&W to verify bonding and brazing techniques and fabrication methodologies. The candidate materials will also be tested in the Hot Fuel Test Rig at UTRC, to establish the effects of heated hydrocarbon fuel on the candidate composite materials to determine if there are leakage problems, swelling, or any other degradation of the candidate composite materials. Following these sequenced subscale tests, fabrication of the jointly designed panels will be performed by SEP. These panels will then be tested in the direct connect, heat-sink scramjet engine test rig at UTRC.

In Phase 2 of AC3, the scramjet combustor component demonstration phase, the four contractors will jointly design a 2-D scramjet combustor. This design will be based upon the conceptual designs developed during the Phase 1 effort, updated for "lessons learned" from the Phase 1 test program. Then SEP will manufacture a rectangular cross-section scramjet combustor, which will be integrally cooled, for testing in a scramjet test facility. This combustor "box" will be incorporated into a direct connect scramjet engine test rig with an upstream fuel supply system which will not be part of this structure. The combustor will then be run to demonstrate closed loop component operation, thermal management, and component/engine performance.

PROGRAM STATUS

Currently AC3 is in the conceptual design effort of the first phase. Conceptual designs of a direct fuel cooled scramjet combustor, manufactured from composite material are underway at both P&W and ONERA, with support from UTRC and SEP. SEP has completed their initial candidate screening efforts for

substrate materials (for the cooled panels and supporting backstructure), anti-oxidation coatings, and anti-porosity coatings. SEP is preparing test samples for P&W's catalyst coating compatibility tests from combinations of these final candidates from these three categories. Testing of these candidates is anticipated to start in June of 1999. Following these tests, which will be completed by July 1999, design and manufacturing of the CHER panels will be started by SEP. The test program for these panels is anticipated to begin in March of 2000 and run through June of 2000. After completion of this test program, Phase 1 will be concluded and Phase 2 will begin.

CONCLUSIONS

The AC3 program is the first attempt to combine composite materials and endothermic fuel cooling technologies into a single, integrated component, a scramjet combustor for an expendable application. The ability to combine these two technologies will result in significant operational and performance benefits for scramjet propulsion systems. With further development, this technology can be extended in application to man-rated, longer cyclic life applications such as manned hypersonic vehicles and gas turbine engines.

ACKNOWLEDGMENTS

The principal author wishes to acknowledge the efforts and support of his team members in this program, from P&W, UTRC, ONERA, and SEP. I also wish to acknowledge the support of the U. S. Air Force Research Laboratory, HyTech Office in this program as provided by Mr. Robert Mercier, Dr. Terence Ronald and Lt. Orval Powell. This is further extended to their counterparts at the French Directeur Generale d'Armements, Ms. Marie Sylvie Amiet, Mr. Roland Favre, and others. This innovative and breakthrough technology development program would not be possible without the help of these persons, as well as the many others who provide the detailed technical support and give generously of their expertise and experience in this endeavor.